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Network management for Mobile Ad Hoc Networks (MANETs) is a challenging management problem given the intermittent connectivity of the nodes and the low bandwidth constraints associated with these networks. Further, MANET management mandates a distributed management paradigm, which gives rise to specific information dissemination challenges. In order to manage these networks, the Network Management System (NMS) needs to send critical network management alerts and data to network operation centers (NOCs) and the NOCs need to send changes to policies and configuration files to the distributed nodes. The need to keep the overhead of management traffic to a minimum and yet reliably deliver this data is a requirement for any NMS in this environment. This paper examines these challenges and proposes an Adaptive Management Plane approach that overcomes these challenges. This approach provides support for Disruption Tolerant Networking (DTN), allowing messages to reach intermittently connected nodes. It also provides a service to deliver management data to the remote nodes according to the information dissemination requirements that regulate the expiration, revision and confirmation of the data. In addition, the approach provides support for above Multi-Topology Routing (MTR), allowing the NMS to deliver data of different priorities over multiple networks that exhibit different traffic delivery characteristics. This solution is described in terms of an implementation in the Dynamic Re-Addressing and Management for the Army (DRAMA) policy-based network management system.

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network operations; MANET; policy-based management; network management; information dissemination

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Using an Adaptive Management Plane for Policy-based Network Management Traffic in MANETs

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Abstract— **Network management for Mobile Ad Hoc Networks (MANETs) is a challenging management problem given the intermittent connectivity of the nodes and the low bandwidth constraints associated with these networks. Further, MANET management mandates a distributed management paradigm, which gives rise to specific information dissemination challenges. In order to manage these networks, the Network Management System (NMS) needs to send critical network management alerts and data to network operation centers (NOCs) and the NOCs need to send changes to policies and configuration files to the distributed nodes. The need to keep the overhead of management traffic to a minimum and yet reliably deliver this data is a requirement for any NMS in this environment. This paper examines these challenges and proposes an Adaptive Management Plane approach that overcomes these challenges. This approach provides support for Disruption Tolerant Networking (DTN), allowing messages to reach intermittently connected nodes. It also provides a service to deliver management data to the remote nodes according to the information dissemination requirements that regulate the expiration, revision and confirmation of the data. In addition, the approach provides support for above Multi-Topology Routing (MTR), allowing the NMS to deliver data of different priorities over multiple networks that exhibit different traffic delivery characteristics. This solution is described in terms of an implementation in the Dynamic Re-Addressing and Management for the Army (DRAMA) policy-based network management system.**

Keyword - network operations; MANET; policy-based management; network management; information dissemination

I. Introduction

Mobile Ad hoc NETworks (MANETs) are characterized by their capability to enable networking without any infrastructure support. Specifically, they are not wired and they have no dedicated routers. As they have no wires, the nodes use wireless radios that are typically characterized by limited bandwidth and typically have high loss rates. In addition, the dynamic nature of tactical MANETs (i.e., nodes intermittently connected) makes it hard to manage their operations in a consistent manner across all network elements.

Command and control applications are challenged when deployed in tactical MANETs due to the constrained communication environment, and the network management systems (NMS) for these networks are also operating under these constraints. In some respects the NMS is more challenged since management traffic is considered overhead and must not add significant traffic to this already bandwidth-constrained environment. The distributed NMS domain for MANETs requires management data be exchanged for several purposes: 1) distribution of new/updated management rules as mission communication requirements change during the mission (in the case of policy-based network management systems this would be the dissemination of new policy rules); 2) distribution of new/updated configuration data when network reconfiguration is required (due to equipment failures and/or revised mission plans); and 3) remote reporting of network alarms/alerts/data to the network operations center for management oversight. A robust and adaptive management traffic solution to address the operational communication challenges of MANETs is a requirement for the NMS.

This paper discusses an Adaptive Management Plane (AMP) to overcome these challenges. The focus of this work is to provide for the efficient, robust, and timely dissemination of management information. This management plane provides an NMS service to deliver management data to the remote nodes according to information dissemination requirements that regulate the expiration, revision and confirmation of the data. It also provides support for Disruption Tolerant Networking (DTN), allowing messages to reach intermittently connected nodes. In addition, the approach provides support for above Multi-Topology Routing (MTR), allowing an NMS to deliver management data of different priorities over multiple networks with different traffic delivery characteristics. Section II provides a review of the goals for the Adaptive Management plane. Section III presents an overview of the NMS used for this work. Section IV presents the AMP Design, Section V is a discussion on implementation and concluding remarks are in Section VI.

II. Goals for the Adaptive Management Plane

In order to design an adaptive management plane for NMS traffic, it was important to identify the key requirements for this communications infrastructure in terms of dissemination

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requirements and networking requirements. These are presented below.

A. Management Information Dissemination Characteristics

The NMS has diverse dissemination requirements for data exchanged between the management nodes. In order to capture these requirements we took a look at the various types of data the NMS exchanges between the distributed management nodes. The reason for doing this was to identify the key dissemination characteristics of the NMS traffic that needed to be supported by the communications infrastructure. The following is a summary of key NMS information classes we analyzed:

- Policies – A policy-based NMS will need to disseminate new/changed policy rules to all nodes. Policy rules need to be consistent on all nodes and the order in which rules are received by a node is important for the semantic integrity of the policy rule database. The distribution of the policy rules is usually done when the rules change; also, activation of rules is expected to take effect immediately.
- Configuration Data – Changes to configuration data and/or configuration scripts must be distributed to nodes. In some cases these changes will need to go to all nodes, and in some cases only a subset of the nodes need to receive the updates. The configuration data can be large (3-10K bytes in size) and often there are multiple files of data that need to be sent.
- Events – Network Management events (alarms/alerts) must be reliably sent to the network administrators responsible for managing the network (i.e., to a centralized NOC). In addition, system-wide changes in mission status that affect networking resources (e.g., change in INFOCON level, change in mission phase) can generate mission events (automatically or user-initiated) that need to be reliably delivered to all or a designated subset of nodes in the network. These mission events are often the trigger for policy rule enforcement. The event messages are typically small in size (less than 1K bytes in size).
- Reports –The NMS will sometimes need to send network management data from the distributed nodes to the network administrators responsible for managing the network.

  Report data (such as SNMP MIB data) may need to be sent periodically to the NOC. If the report for a particular time-interval cannot be delivered to the NOC (due to limited connectivity and/or reduced bandwidth), and a new report is available for a subsequent time interval, the NMS may want to only send the most current report. This capability will make more efficient use of the limited bandwidth available in an ad hoc network. In addition, some reports are not useful if they are not received at the destination within a specific amount of time after the generation of the report. The capability to expire a report (and not send the outdated data) is another capability that is useful in this bandwidth-limited environment.

Based on the above characterization of the data, we were able to identify (10) attributes of the data (e.g., confirmation messages, new data overrides, data not yet sent, expire data, etc.) that are key capabilities that will need to be supported by the communications infrastructure for NMS traffic. Table I below captures these attributes for each of the information classes we analyzed.

TABLE I. NMS TRAFFIC ATTRIBUTES

Type of Data	Size	Frequency	Timeliness ?	Later Data Overrides	Order?	Reliability	Confirmations?	Scope	Expire?	Compression?
DRAMA Policies	S	- On-demand - At mission start can be	Immediate	Sometimes	Y	H	N	ALL	N	N
Configuration Files	L	- On-demand - At mission start can be bursty	Sometimes done in advance of use	Yes	Y	H	Y	ALL and/or Selected	Maybe	Y
Scripts	M-L	- On-demand - At mission start can be bursty	Sometimes done in advance of use	Yes	Y	H	Y	ALL and/or Selected	Maybe	Y
Events	S	- OnDemand - Bursty - Periodic	Immediate	No	Y	H-M	N	ALL and/or Selected	Y	N
Query/Request	S	- On-Demand	Immediate	No	Sometimes	M-L	N	ALL and/or Selected	Y	Maybe
Reports	S-L	- OnDemand - Bursty - Periodic	Imnediate (On-demand rpts) Background (Periodic rpts)	Maybe	N	M	N	Send to TOC	Y	Maybe
Rules/Settings	S-M	- On-Demand	Sometimes done in advance of	Yes	Y	H	Y	ALL	N	N
Network Plans	L	- On-demand - At mission start can be bursty	Sometimes done in advance of use	Yes	Y	H	Y	ALL	N	Y

These attributes provided the requirements for AMP's data distribution service as it relates to the wide range of NMS message traffic.

B. *Networking Support*

In addition to the dissemination requirements described above, we investigated two networking technologies that are applicable to airborne military ad hoc networks. Our goal was to incorporate technologies that are relevant to the limited end-to-end connectivity in the airborne network and to the multiple radio links on the airborne network nodes that can provide for prioritized network operation communications.

1) *Disruption-Tolerant Networking (DTN) Technology*

Disruption-tolerant networking research [1] [2] [3] [4] [5] and [6] has been focused on the delivery of messages where the nodes in the network are intermittently connected and the network does not provide end-to-end connectivity for a significant amount of time. Such networks, which include airborne networks under certain circumstances, pose some major challenges. The first challenge is that traditional reliable network transport protocols such as TCP cannot be used as they require end-to-end connectivity. The second challenge is that of message buffering and message forwarding, as packets may need to be stored by an intermediate forwarding entity when there is no route to the destination until such a route becomes available.

While utilizing store-and-forward technology does provide benefits, especially in dealing with the lack of end-to-end connectivity of nodes in airborne ad hoc network, it is also a challenging requirement. The topology of the nodes is not known a priori; and therefore determining the appropriate forwarding entity (entities) needed to deliver the data to the destination node(s) is a difficult problem. Given that the best store-and-forward route to the destination node is not known ahead of time (and if it is known, it is not guaranteed to remain exactly as planned), it is therefore necessary that the NMS dynamically learn the appropriate "store-and-forward topology" of the network.

2) *Multi-Topology Routing (MTR) Technology*

Multi-topology routing introduces the capability to configure service differentiation through class-based forwarding. MTR has been published by IETF as RFC 4915 [7] and has been supported by major manufacturers including Cisco and Juniper. MTR provides multiple logical topologies over a single physical network. Service differentiation can be achieved by forwarding different traffic types over different logical topologies that could take different paths to the same destination and thereby result in different loss and delay characteristics due to different link-layer and physical layer technologies over these paths [8].

Utilizing MTR capabilities in the network provides mechanisms for the NMS to prioritize management traffic. Traffic can be marked with different DSCPs by the NMS to use different network paths to best meet their distribution requirements. For example, for information that is not latency-sensitive but requires relatively reliable delivery, a satellite link could be the best transmission choice. The NMS can monitor the condition of different radio networks to make information distribution decisions based on the various criteria discussed earlier in this section.

III. THE DRAMA SYSTEM

The NMS capability described in this paper is implemented in the Dynamic Re-Addressing and Management for the Army (DRAMA) system. Telcordia Technologies developed policy-enabled intelligent agent technologies for the U.S. Army Communications Electronics Research and Development Engineering Center (CERDEC) under the DRAMA Science and Technology Objective (STO) to cope with the unique management challenges posed by the future military tactical networks [9] and [12]. After the DRAMA technology was successfully demonstrated as a solution for the Army tactical network domain, the Air Force Research Laboratory (AFRL) subsequently leveraged the Army's investment in its NATM program [10] and [11] to investigate its suitability as a solution for network management in the airborne network domain, which culminated in the Government's successful employment of the DRAMA/NATM technology in three live-fly demonstration events.

The DRAMA system employs a distributed-agent architecture, and possesses self-adapting, self-organizing, and self-healing capabilities that are essential for managing dynamic military tactical networks. The DRAMA system features policy control, which allows networks to be managed by policies that can be tailored for different missions. The policy agents in DRAMA are organized into a tree-like management hierarchy. The purpose of this organization is to create a hierarchy of distributed managers as depicted in Fig 1. At the leaves of the tree will be the Local policy Agents (LPAs) that are responsible for gathering status and managing networking elements on the local node. Domain Policy Agents (DPAs) are intermediate nodes in the tree hierarchy; they receive summarized reports from subordinate DRAMA instances (LPAs) and manage local elements. DPAs report the combined status of their local elements and their subordinate reports to their respective masters, which could be other DPAs or the Global Policy Agent (GPA). At the top of the hierarchy is the GPA that receives reports from subordinates and forms the root of the tree.

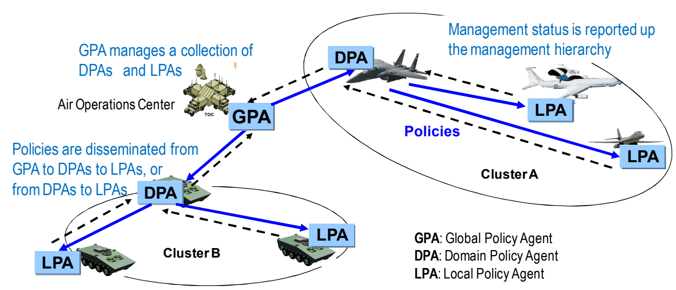

Figure 1 – DRAMA Management Hierarchy

DRAMA is a policy-based network management system. Policy rules are triggered by Events, limited by Conditions, and result in enforcement of Actions (thereby sometimes referred to as **ECA** rules). The DRAMA policy management function listens for events. When it detects an event that matches that of an active policy, the policy management function triggers the policy. Inactive policies are never triggered. When a policy is triggered, the policy management function evaluates the conditions specified in the policy. If the conditions of a triggered policy hold (are true), the policy management function enforces the policy by taking the actions specified in the action section of the policy.

IV. DESIGN OF THE ADAPTIVE MANAGEMENT PLANE

The Adaptive Management Plane (AMP) in DRAMA provides the communications support for network management traffic. This communications support is provided by both the CommStack software (within the Hierarchical Group Infrastructure component) and the AMP Distribution and Transport layer components. CommStack communications is a distribution mechanism that was described in an earlier paper [13] See Fig. 2 below for an overview of the AMP components.

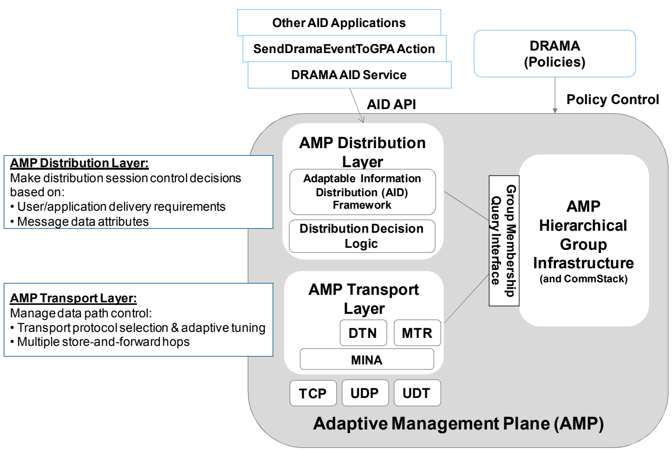

Figure 2 – DRAMA AMP Components

DRAMA supports the following messages between DRAMA nodes:

- GPA messaging (sending data to the centralized NOC)
- File/Event distribution messaging
- Policy rule distribution messages
- Hierarchy formation messages.

For the first two items (GPA messaging and File/Event distribution), DRAMA was enhanced to use AMP communications and this messaging is the focus of this paper. DRAMA was extended to provide a communications service that is callable by other DRAMA components. The API that is used to call this communications service is referred to as the Adaptable Information Distribution (AID) API. In addition, another AMP API is available to allow policy actions to control some aspects of AMP communications. This API allows policy rules to be written to autonomously control the behavior of the AMP (e.g., turning data compression on/off based on network conditions, tuning rescan intervals, etc…).

The 3rd item (policy rule distribution messages) uses the legacy CommStack communications in the Hierarchical Group Infrastructure component. During this phase of AMP implementation we did not change the communications mechanism for this data. We expect that future work will address this support. The last item (hierarchy formation messages) will not use AMP since these messages provide the basic node/cluster information needed by the AMP infrastructure that will be discussed in this paper (see the AMP Hierarchical Group Infrastructure section below).

A. AMP Hierarchical Group Infrastructure

The Hierarchical Group Infrastructure (HGI) component is used to create a hierarchy of distributed managers. More specifically, the clustering algorithms in this component are the mechanism that allows the distributed nodes to form a management hierarchy. A cluster is a set of nodes arranged in hierarchy up to a root. If the network becomes partitioned (e.g., due to mobility), there will be multiple clusters. When nodes in one cluster move within communications range of another cluster, the HGI components merge the clusters.

This component contains the clustering algorithms that use: 1) heartbeat messages (to determine the connectivity to children) and 2) probing messages (to find a parent) in order to maintain the management hierarchy. In addition, this component exchanges additional messages (clustering messages) which are sent up the hierarchy with grandchildren information. As the messages go up the hierarchy, these messages then contain information about grandchildren, great-grandchildren, etc. When the information reaches the root of cluster, the cluster-wide view of all the nodes is available. The root's view of the set of nodes in its cluster is periodically sent to down the hierarchy to all the nodes if that data has changed.

The HGI component supports the AMP Distribution and Transport layers. For the AMP distribution layer, this component provides membership information. For example, when the AMP distribution layer needs to resolve a reserved name (i.e., PARENT, CHILDREN, ALL, ALL-SATCOM) into a list of specific node names, it is this component that provides that functionality. In addition, this component provides current cluster information to the AMP distribution layer. For example it provides the list of nodes in current cluster.

The HGI component also provides historical clustering information to the AMP transport layer. For example, when the AMP layer needs to determine the next hop in a DTN distribution, it is the HGI component that has the historical view of what other clusters the destination node has been a part of and the historical members of those clusters. Using this information, the HGI component can provide a list of nodes that can possibly be used as the next hop to reach a node not currently in the sending nodes cluster (further information on the DTN support is discussed below).

B. AMP Distribution Layer

The AMP distribution layer's primary objective is to provide bandwidth-efficient, robust message delivery to recipient(s). To do this, the AMP distribution layer is responsible for two functions: 1) providing an adaptable information distribution framework needed to fulfill the delivery requirements of the data (e.g., confirmations, expiration, replacing updated data if not yet sent, etc…) and 2) determining whether DTN or MTR should be invoked before passing messages to the message transport layer.

1) Adaptable Information Delivery (AID) Framework

The AID framework is composed of two major components: AidChannel and AidLayeredStack. AidChannel interfaces with the AID client to send/receive messages and the AidLayeredStack processes messages.

An AID client sends and receives messages through an AidChannel. Each AidChannel is equipped with an AidLayeredStack. The stack contains a stack of message processing layers. The following processing layers are defined:

- Confirmation Layer – on the receiving end, this layer generates an AIDConfirmation message to the sender of the AIDMessage, if the AIDMessage is marked as "confirmation needed". On the sending end, this layer forwards the confirmation up to the Application, if the message is marked as "confirmation needed".
- Compression Layer – this layer compresses the outgoing message and decompresses the incoming message, if the message requested compression.
- Expiration Layer – this layer drops incoming messages that have expired.

This framework also provides the capability to "update" messages in the outgoing queue. When an application wants to update a previous send message request with newer content, the client uses the same message ID (AID returns a message ID to the client when called to send data) and calls the AID framework with the new content and new expiration time. The recipients and delivery confirmation are copied over from the previous send request.

a) Policy Control of AMP

The AMP provides an API to change various AMP parameters for one or more channels (e.g., turning data compression on/off based on network conditions, tuning interval which the transport layer with retry sending messages in the transport queues, etc.). This API was used in a new DRAMA action (AidChannelConfigurationAction). In this way a DRAMA policy rule can be written to allow automatic (based on network conditions/events) or network administrator-initiated (based on manual trigger event) triggering of this action. In this way the AMP communications can adapt to network and mission conditions.

2) Distribution Mechanism Selection

The AMP distribution layer also is responsible for determining whether DTN or MTR should be invoked before passing messages to the message transport layer.

a) MTR Decision

AMP messages can have a client-specified priority. In the current implementation of DRAMA, we support SATCOM and NON-SATCOM priorities. If the DRAMA installation is configured with SATCOM interfaces on one or more of the nodes, then the MTR capability can be used. When a SATCOM distribution is requested by the client, the distribution layer will mark these messages for MTR processing and pass the messages to the AMP transport layer.

a) DTN Decision

If a NON-SATCOM message is to be sent, the AMP distribution layer will determine whether the message should use the DTN for transport. For each destination in the request, this function will first see if it has connectivity to that node using its current cluster information. If it does, it will send that request to the AMP transport layer for non-DTN processing. If the destination is not in the current cluster then the message is marked for DTN processing by the AMP transport layer.

C. AMP Transport Layer

The AMP Transport Layer's primary objective is to provide end-to-end message data path control above the network transport protocols (e.g., TCP, UDP, etc.). This layer provides a persistent store for all outgoing messages. The messaged are safe stored so that messages are not lost across DRAMA restarts and when nodes are disconnected. When messages are received by this layer, they are placed in queues for processing. There are currently three queues that this layer services: 1) Direct queue, 2) MTR queue and 3) DTN queue. Messages are not deleted from the queue until they have been successfully delivered to either their destination (Direct/MTR queues) or to their next hop (DTN queue). Messages in the Direct Queue are sent to the destination node using their AidChannel.

a) MTR Transport

As mentioned earlier, MTR provides mechanisms for the NMS to prioritize management traffic. Traffic can be marked with different DSCPs by the NMS to use different distribution paths to best meet their distribution requirements. During DRAMA startup, MTR pre-processing will take place if any DRAMA AidChannels have been defined with SATCOM transport. The properties for these SATCOM AidChannels will be read in by the MTR pre-processing function. This function will then install ipTables rules based on these properties. These rules will mark any packets that contain the port and protocol of a SATCOM AidChannel with a specific TOS bit setting (DSCP value). Thus with the capabilities of an MTR-enabled network, these messages can be delivered over a different distribution path than NON-SATCOM messages. Messages in the MTR Queue are sent to the destination node using their AidChannel.

a) DTN Transport

DTN transport focuses on the delivery of messages where the nodes in the network are intermittently connected and the network does not provide end-to-end connectivity for a significant amount of time. At the AMP transport layer the next hop for the message must be determined. The next hop for a message is determined using cluster information provided by the AMP HGI component.

The HGI component maintains current cluster information as well as historical cluster information. When the AMP transport layer sends a "*get-next-hop*" request to the HGI component, the HGI component will return a weighted list of possible next hops.

For example, suppose we are trying to send data from the source (node S) to the destination (node D), over an intermittently connected network (as shown in Fig. 3,). In this network the connectivity is such that we have (3) clusters (S, c and g). We have two nodes that transit between the clusters (nodes f_a and f_z). This node intermittently appears in clusters S, C, and g (not at the same time). Nodes f_a and f_z can be viewed as the "ferry" nodes that can transport the message to the destination (and in reverse ferry the confirmation back to source node if requested).

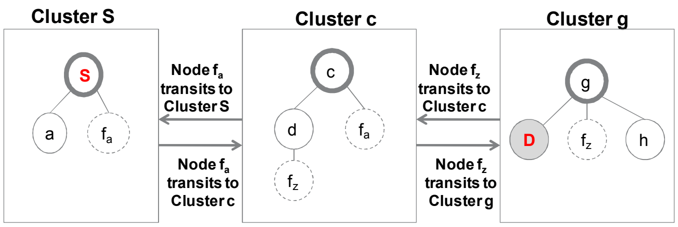

Figure 3 – DTN Clusters

The HGI component will determine the list of nodes that have transited to the destination cluster (the cluster that contains the destination node) at some point in the past, as well as any intermediate clusters that the nodes in the destination cluster have belonged to at some point in the past. This list of nodes will be weighted by when they were last in the destination cluster (i.e., exit time) and how long they were in the destination cluster (i.e., duration). If no nodes are returned, the transport layer will leave the message in the queue until the next retry interval. If the one or more nodes are returned, the transport layer will select the highest weighted node to be the next hop to get the data to the destination, and will send the data to this next hop. This *get-next-hop* processing is repeated at each intermediate destination.

V. Implementation

We have performed initial testing of the AMP functionality in the DRAMA system over a simulated radio network implemented in the Virtual Ad-Hoc Network (VAN) testbed [14] with simulated airborne platforms on a radio network. The simulation model chosen for the wireless network was the Wireless Transport Network developed by Avaliant, LLC.

Our simulated environment consisted of a 10-platform wireless network. The simulation scenarios included movement of the platforms to create various arrangements of intermittently connected nodes on the network. In all cases the DRAMA messages/files were successfully delivered to the destination platform(s).

VI. Summary and Future Work

The Adaptive Management Plane provides a communication service for network management traffic that is capable of dealing with the intermittent connectivity and low bandwidth requirements of tactical military mobile ad hoc networks. In addition, the AMP provides information dissementation capabilities that are applicable to network management traffic. AMP functionality has been implemented and tested on simulated wireless networks with good results.

Future work will include further testing of the AMP functionality and performance testing of the functionality in the simulated network.

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